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ICG Real-Time Stereo Dome Projection System

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1 Introduction

The dome is a medium of illusion, immersion and dissolution. In its ideal form, sphere or hemisphere, and without edges, it is ideally suited to hide or withdraw its own corporeality and yet it remains a defined three-dimensional space that visitors can enter physically. The history of the dome begins with the Pantheon, the first superlative that was completed under Emperor Hadrian 128 b.c. The 18th and 19th centuries brought the first industrial forms of mass media that are in close proximity to the dome projection we know today and are often considered to be precursors of cinema: the panorama at the end of the 18th century that formed a first standardized medium. Quickly, construction processes and screen sizes were standardized, so that the panoramic paintings could be presented around the world, similar to a film copy that is shown in cinemas. In 1923, the first *Zeiss* planetarium had its test run on the rooftop of the Zeisswerke and set a worldwide standard for planetary demonstrations with its design of the movable optical projection apparatus and its unparalleled image quality that could hardly be surpassed until today. The viewers of the contemporary projection domes of the IMAX cinemas or planetariums face a problematic position: it remains their duty to position themselves with respect to the projection. In planetariums, this usually happens in a poly-directional orientation of the auditorium below the projection dome, within a circle around the centrally placed star-shaped projector that always occludes parts of the picture. On the other hand, IMAX and other cinemas have a unidirectional orientation of the auditorium towards a sloping dome. In these *crafted spaces*, the spectators can move freely within the framework of the architectural specifications. Thus, each viewer has a different perspective on the pictorial event, and it is never possible for more than one person to occupy the optimal viewing position in the sense of a central perspective illusion. The projection into the dome takes an extreme position among media presentation commodities: under certain circumstances, part of the action takes place in the dome behind the back of the viewer or directly above them. Perspectively constructed still or moving pictures usually put the spectators in an unfavorable perceptual position. Only one seat, one point of view, provides the optimal projection since the point of view within the central-perspective construction coincides only with exactly one point in the three-dimensional space of the audience. With regard to the perceptual situation of the observers within the dome space, the central-perspective construction as a means of immersion, creates a difficult situation that implies the necessity to design the viewing experience as an individual one, which, however, is hardly economical.

Fast forward to the present day, introducing the *ICG Dome*, a research facility crafted for research of immersion, presence and behaviour in virtual worlds that solves every issue at once with state-of-the-art technology. Featuring the latest motion and eye tracking systems and high-speed projection

systems, the dome is capable of dynamically presenting immersive multi-user environments while maintaining perceptually correct viewing perspectives. The ICG Dome empowers researchers of human computer interaction, computer and life sciences and the human visual system alike to overcome the limits of current immersive technologies that are still limited in field of view and interaction.

This technical report introduces the ICG Dome research facility at the *Institut für Computergraphik* located in Braunschweig, Northern Germany. Related projects, publications and current information will be released under <https://graphics.tu-bs.de/projects/icg-dome>.

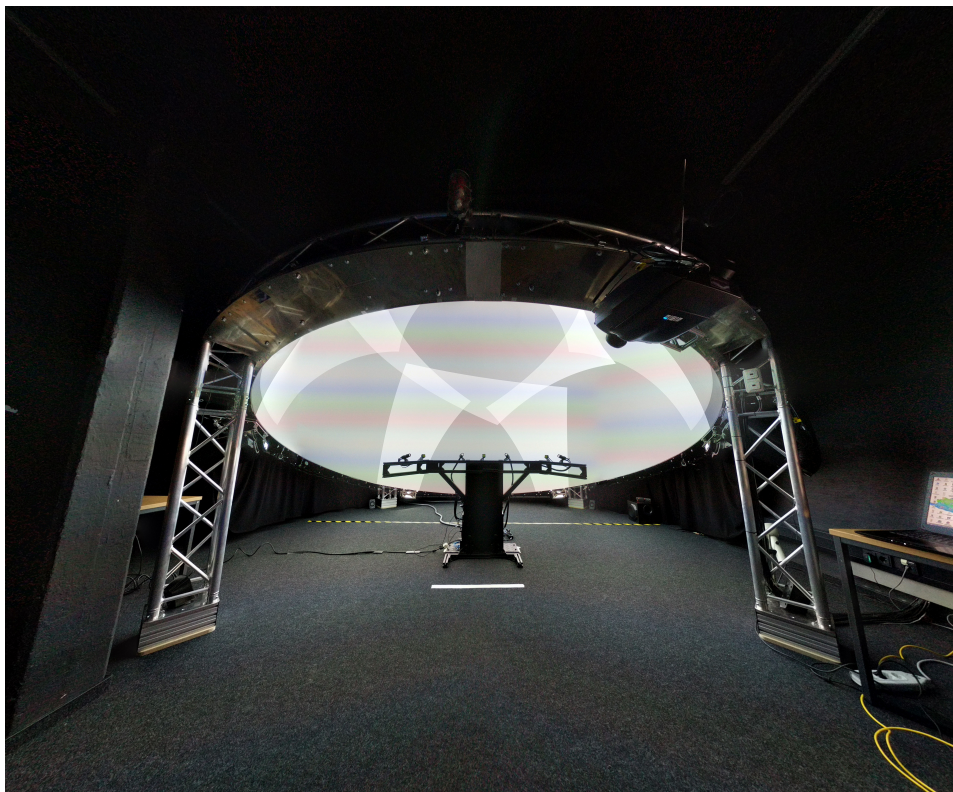


Figure 1: The ICG Dome

2 System Overview

The *ICG Dome* is a real-time full-dome video projection system featuring dynamic stereo, motion capture and eye tracking.

The dome sphere has a diameter of 5 m and is built from 8 individual glass-fibre reinforced plastic slices assembling a seamless hemispherical screen surface without any visible disruptions. It is tilted backward by 20°

such that the rear side almost touches the floor while the front side reaches a height of ~ 1.9 m, as depicted in Figure 2. It is equipped with six *projectors* mounted at the equatorial line. The projected images cover the entire dome surface (the field of view of the notional cameras called frustums are shown in red in Figure 2). Each projector is connected to an individual machine (*rendering node*) to distribute the compute workload. An additional machine (hardware-equivalent to the render nodes) serves as operator and developer workstation and will be referred to as *master node*. Furthermore, six infrared cameras are used for *real-time motion capture* and four additional cameras allow *real-time eye tracking*. The eye tracking system as well as the motion capture system are powered by separate dedicated machines. All computers are connected via a dedicated isolated Gigabit-Ethernet local area network (LAN). Visual content is rendered using a custom-built

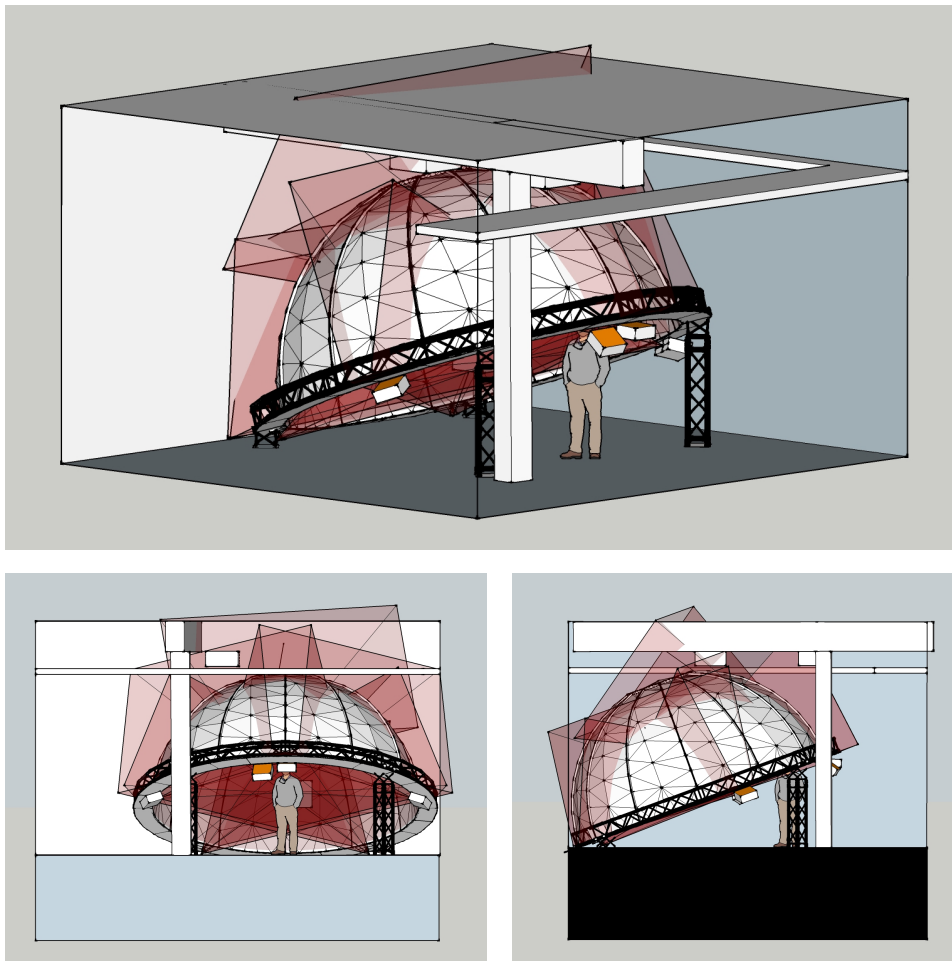


Figure 2: Construction of the dome system

cross-platform *OpenGL*-based rendering framework. All machines run the Microsoft Windows operating system.

Synchronization The distributed nature of the rendering system architecture requires real-time synchronization. Application synchronization between all machines is managed using *barriers* from the Message Passing Interface (MPI). MPI is a communication protocol for programming parallel computers and is the de facto standard in high performance computing. It is a message-passing application programming interface, together with protocol and semantic specifications. The program control flow also follows the MPI paradigm. All involved machines execute the same code — differences during execution depend solely on their *rank* within their synchronization group. The render nodes form a synchronization group. Within a group, all processes must reach common point in their code before they can continue execution again. A designated *master* node with the special *rank* of 0 distributes runtime-generated data like user input to the render nodes with a rank > 0 . Static data like scene content and other assets are distributed to the render nodes via a common network share. Additionally, the master node receives data from eye and motion tracking systems and distributes it to ensure that all machines use the exact same tracking information.

3 Components

Projection The system features six *Barco F50 WQXGA projectors* with a resolution of 2560×1600 pixels (WQXGA), a frequency of up to 120 Hz and a contrast ratio of 5 300:1. The images of five projectors cover the bottom segment of the spherical dome surface, as shown in Figure 3 (left), including enough overlap for smooth blending between neighboring projections. The sixth projector points toward the dome ceiling to cover the remaining spherical cap (Figure 3 right) of the dome surface. Each projector is driven by a dedicated *Dell Precision Rack 7910* workstation equipped with an *Intel Xeon E5-2643 v3 CPU* (3.40 GHz, 32 GB RAM) and an *Nvidia Quadro M6000 GPU* (12 GB RAM).

Eye Tracking A *Smart Eye Pro*¹ system enables real-time binocular eye tracking with four industry-class cameras running at 120 Hz within a field of view (FOV) of approximately 160° in horizontal and 90° in vertical direction with an accuracy of 0.5° (under optimal conditions). The system estimates head position and orientation, eye positions and gaze directions for the left and right eye. Tracking data is broadcasted via the network using the UDP protocol in real-time.

¹<http://web.archive.org/web/20171114174720/http://smarteye.se/wp-content/uploads/2016/10/Smart-Eye-Pro.pdf>

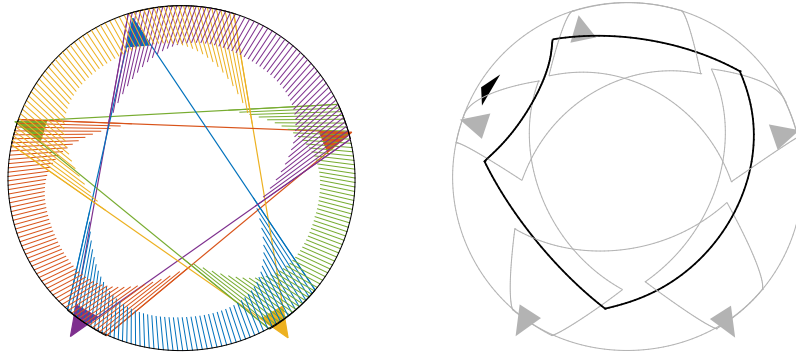


Figure 3: Top views showing five projectors (solid triangles) covering the lower spherical segment of the dome (left) and the sixth covering the spherical cap (right)

Motion Capturing Real-time motion capturing is implemented with a marker-based *OptiTrack* system and six *OptiTrack Prime 13W*² cameras. The system tracks the position of individual infrared retro-reflective spherical markers with sub-millimeter precision at 240 frames per second (fps). Physically fixed groups of three or more markers may form trackable rigid bodies with known spatial orientation. A second isolated LAN is dedicated to the communication between the cameras for the motion tracking system.

4 Image Generation

The projected images create a seamless 360° panorama of a 3D scene with the point of view aligned to the viewer's head. Viewing position is a crucial factor within the dome environment, especially with the spherical projection surface. The rendered visual content needs to be synchronized to the spectator's point of view to not appear distorted and out of place. Therefore, head position tracking is done in real-time using either markers attached to the viewer's head or the head position estimation of the eye tracking system. The head position is distributed to all render nodes in real-time and is used to update the camera position within the scene to provide a consistent close-to-real viewing experience. For this purpose, each rendering node performs the following three steps: First, a dynamic virtual camera frustum is calculated to cover the (per projector) corresponding area of the dome surface from the viewer's point of view. Second, the conventional rendering of the scene content is stored in an intermediate frame buffer. Third,

²<https://web.archive.org/web/20171028043008/http://www.optitrack.com/products/prime-13w/specs.html>

the intermediate image is warped onto the dome surface, as seen from the projector (user-to-projector perspective).

For the monocular case, the point of view is set halfway between the position of both eyes of the viewer. Extensions for the binocular (stereo) rendering case are described in later sections.

Dynamic Frustum Alignment The dynamic virtual camera frustum keeps its origin aligned with a viewer's head position to enable free movement with real-time motion parallax. Therefore, the virtual camera is placed at the viewer's tracked eye or head position as shown in Figure 4. The virtual

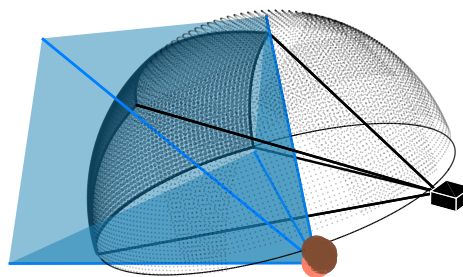


Figure 4: Virtual camera frustum and corresponding projector frustum

camera's frustum is frame-wise reoriented according to new head or eye tracking data and the projector position within the dome relative to the user. First, the camera is oriented to face along the projection area's *approximated normal*. Second, the projection matrix is created using 8 reference points at the border of the projection area (surface patch). The simplest solution is to use the four corner points of a projector's projection area that are known by the vendor's system-wide proprietary calibration procedure but this may not result in sufficient coverage of the projection area: Depending on the position of a virtual camera relative to its corresponding dome surface patch, the edges of the patch may bend outside the rectangular bounding box created by the corners due to barrel distortion. An extreme example is shown in Figure 3 (right). Here, dome produces strong barrel distortion for the projection area of the sixth projector (black outline). Additionally including the midpoints of the borders results in sufficient coverage as the bounding boxes always include the whole projection area. The remaining missing regions are small enough to be handled through overlap and blending between projectors.

Generating a single frustum to cover full projection areas introduces another problem. If the user moves too close toward the dome surface (i.e. backward or sideways) the opening angle of the virtual camera's frustum of the of the corresponding projector gets close to or even exceeds 180° as in Figure 5 (right). This results in numerically unstable or completely invalid

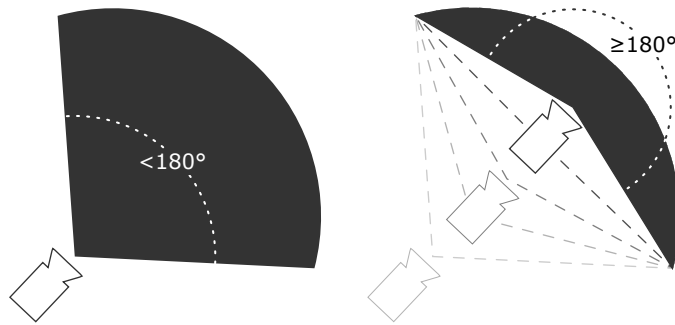


Figure 5: Head / virtual camera positions resulting in valid (left) and invalid (right) frustums with opening angles close to or above 180°

projection matrices. We mitigate this issue by subdividing the frustum into six equally-sized sub-frustums for each projector as depicted in Figure 6. Each sub-frustum has its own approximate normal and camera rotation.

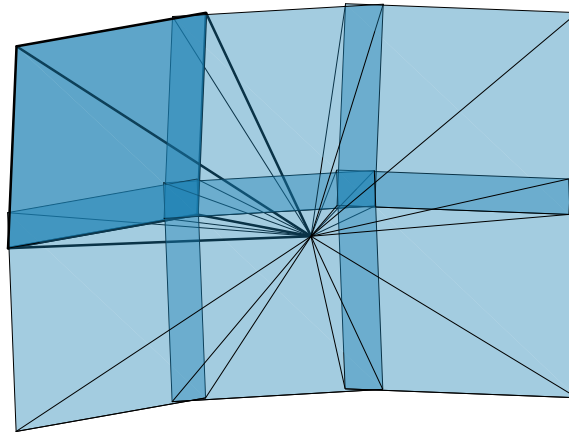


Figure 6: Subdivision of an invalid frustum into six smaller sub-frustums. The first of six sub-frustums is exemplary shown in the upper left corner.

Using asymmetric sub-frustums is sufficient to constrain their opening angles to valid sizes. Artifacts in the resulting image along edges between sub-frustums are avoided by creating an ~ 80 pixel overlap between each other to allow for smooth blending as shown in Figure 6.

Warping Warping transforms a conventional rendered 2D image of a scene for projection onto the curved dome surface for distortion-free presentation. This additional step is necessary because intermediate images rendered for the virtual camera are not seen from the real projector's point of view. Thus, the warping step transforms a rendered image from the virtual camera's view

into the projectors view space with respect to the curved dome surface.

A 3D mesh that represents the corresponding dome surface patch is rendered from each projector's point of view, as shown in Figure 7. Each vertex of the surface geometry is then projected into the intermediate user-view image for texture lookup.

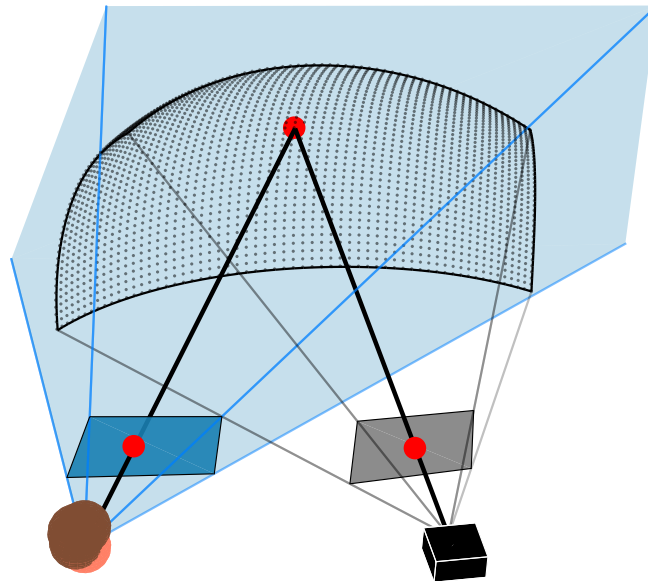


Figure 7: Warping pixels from virtual camera output to projector space via 3D mesh of the dome surface

Stereoscopies Stereoscopy (also called stereoscopies, or stereo imaging) is a method for creating or enhancing the illusion of depth in an image by means of stereopsis for binocular vision. The dome projectors implement stereoscopic imaging via two individual screen input sources (60 Hz maximum) that are connected to the same graphics card of a rendering node. In stereo mode, the projector utilizes both input sources and alternates between the two input images. The stereo effect is implemented using synchronized shutter glasses. A shutter system works by openly presenting the image intended for the left eye while blocking the right eye's view with a liquid crystal layer, then presenting the right-eye image while blocking the left eye. This is repeated very rapidly so that the interruptions do not interfere with the perceived fusion of the two images into a single 3D image.

The render nodes are used in dual-screen mode with extended desktop configuration such that each graphics card output carries a different image. A fullscreen window is created for both screens by our custom-built rendering software. The virtual scene is rendered for both actual tracked eye positions.

Blitting the second eye's view into the second window, we render within the same OpenGL context and thus avoid having to duplicate scene objects.

Resolution The resulting resolution was determined to be ~ 8855 pixels in horizontal and ~ 4575 pixels in vertical direction. The resolution was estimated using a horizontal and vertical plane passing through the observer's position (projection center). During rendering, these planes appear as lines. The six individual projector images were used to measure the pixel distance as the number of projected pixels along these lines. Additional visual markers on the planes allow to estimate the pixel distance through multiple projector images and along warped lines. This leads to an average angular resolution of ~ 38 pixels per degree in the foveal region and ~ 22 pixels per degree in the periphery (90°).

5 Latency Test

For evaluating the latency of the distributed rendering system, we constructed a small *measurement device* based on an *Arduino Uno Rev3 (ATmega328P)* equipped with a phototransistor that captures the delay of changes in brightness, i.e. screen content changes independent of the rendering application. The device is connected to the master node via serial connection using an *Arduino Shield RS232* for real-time communication. The projected solid-colored fullscreen content in the phototransistor-observed area is programmatically flipped from dark to bright (black to white). At the same time a serial trigger signal informs the Arduino timer about the requested change in brightness and starts measuring the delay between the rising serial trigger and phototransistor edge. We used a dark to bright sequence as optical trigger because our circuit has faster response times for this transition direction. The intrinsic measurement device-specific communication round-trip delay was estimated with repeated signal echo tests beforehand and is included for correction of the resulting timings: Measurement device delay average ~ 6.28 ms, standard deviation ~ 1.85 μ s, $n = 500$.

Additionally, the threshold between dark and bright varies due to several conditions and is therefore determined during the initialization phase of the measurement process to handle e.g. individual changes in projector brightness. With the process described above, we estimated the system rendering latency (excluding external tracking systems) from $n = 157$ measurements: average ~ 50.22 ms, standard deviation ~ 4.62 ms, $n = 157$.

While most delay is introduced by the internal processing speed of the projectors, no measurable delay was introduced via distributed rendering and synchronization. This was evaluated with the same test executed on a single render node with all MPI functionality switched off resulting in similar timings.

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